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Original Article

NUCLEAR FUEL CYCLE COST ESTIMATION AND SENSITIVITY ANALYSIS OF UNIT COSTS ON THE BASIS OF AN EQUILIBRIUM MODEL

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ABSTRACT

This paper examines the difference in the value of the nuclear fuel cycle cost calculated by the deterministic and probabilistic methods on the basis of an equilibrium model. Calculating using the deterministic method, the direct disposal cost and Pyro-SFR (sodium-cooled fast reactor) nuclear fuel cycle cost, including the reactor cost, were found to be 66.41 mills/kWh and 77.82 mills/kWh, respectively (1 mill = one thousand of a dollar, i.e., 10^{-3} \$). This is because the cost of SFR is considerably expensive. Calculating again using the probabilistic method, however, the direct disposal cost and Pyro-SFR nuclear fuel cycle cost, excluding the reactor cost, were found be 7.47 mills/kWh and 6.40 mills/kWh, respectively, on the basis of the most likely value. This is because the nuclear fuel cycle cost is significantly affected by the standard deviation and the mean of the unit cost that includes uncertainty. Thus, it is judged that not only the deterministic method, but also the probabilistic method, would also be necessary to evaluate the nuclear fuel cycle cost. By analyzing the sensitivity of the unit cost in each phase of the nuclear fuel cycle, it was found that the uranium unit price is the most influential factor in determining nuclear fuel cycle costs.

1. Introduction

Because not many reprocess facilities or enrichment facilities exist in nations with advanced nuclear power generation technology, the data related to the nuclear fuel cycle cost are mostly estimated costs instead of real costs [1]. Further, it is very difficult to obtain the relevant costs. Thus, the nuclear fuel cycle cost as an estimated cost is inevitably subject to uncertainty. A probabilistic method is generally used to evaluate such uncertainty. Namely, an input variable with a

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high uncertainty is assumed to have a probability distribution, and the result of the calculation is assessed through this distribution. If the decision makers involved in the policies of nuclear fuel cycles know the result of the nuclear fuel cycle cost calculated by the probability distribution, they can make better decisions by referring to the standard deviation value including uncertainty. However, most nuclear fuel cycle costs have used a deterministic method thus far. In this case, a deterministic method means calculating the nuclear fuel cycle cost using an input variable as a representative value instead of a probability distribution [2].

In addition, such uncertainty cannot be considered in the deterministic cost estimation [3], because the result calculated by the deterministic method produces the nuclear fuel cycle cost as a value instead of a probability distribution. Therefore, not only a deterministic method, but also a probabilistic method that uses a probability distribution, is necessary in the engineering cost estimation method based on a conceptual design [4].

The back-end nuclear fuel cycle cost that includes the cost to manage spent fuel (SF) is also subject to high uncertainty. For example, the cost caused by subsequent action for serious and unexpected accidents like the Fukushima Nuclear Power Plant in Japan increased the uncertainty of the nuclear fuel cycle cost. If the premium for a nuclear power plant accident and indemnity money paid to the community to acquire the site of the high-level waste (HLW) repository is included in the nuclear fuel cycle cost, the current nuclear fuel cycle cost will increase considerably [5]. After all, the economic efficiency of nuclear power will decrease if such a social cost is included in the cost to dispose of SF. Social cost means the cost to hold public hearings so as to acquire the site of the repository or indemnity money paid to regional residents or the community.

Furthermore, the data related to the nuclear fuel cycle may vary considerably, because the measuring environment is different in each country [6]. Cost may also vary, depending on the effect of scale in the difference of capacity of a nuclear fuel cycle facility [7]. Thus, it is necessary to convert the nuclear fuel cycle unit cost with high uncertainty into reliable information through normalization.

This paper reports on an examination into the influence that the uncertainty of the parameter used in the equilibrium model of the cost evaluation has on the nuclear fuel cycle cost.

In addition, we clarified which unit price has the most influence on the nuclear fuel cycle cost by analyzing the sensitivity of the unit cost in each phase of the nuclear fuel cycle. Namely, the uncertainty of the parameter that considerably affects the nuclear fuel cycle cost is quantitatively indicated by calculating the contribution to the variance.

2. Materials and method

2.1. *Nuclear fuel cycle cost estimation: three options*

To calculate the nuclear fuel cycle cost using the equilibrium model, this study set three nuclear fuel cycles [pyro-SFR (sodium-cooled fast reactor), PWR-MOX (pressurized water reactor, mixed oxide fuel), and direct disposal] as the target of the analysis.

Massachusetts Institute of Technology (MIT), Cambridge, MA, USA [4] evaluated direct disposal as the most economical option. Further, the PWR-MOX nuclear fuel cycle can use an aqueous reprocessing method that was most prevalently used in nations with advanced nuclear power generation technology [8], and the Pyro-SFR nuclear fuel cycle is currently being recognized as a nuclear technology of the future as well as an advanced nuclear fuel cycle.

In particular, the Pyro-SFR nuclear fuel cycle is highlighted as a competitive alternative to direct disposal in terms of economic efficiency, because an efficient reprocessing method is being re-examined in many states of the world, such as the cancellation of the Yucca Mountain Repository project in the United States. Furthermore, we cannot be certain that direct disposal is more economical than the Pyro-SFR nuclear fuel cycle alternative when considering the social cost of a HLW repository, because the direct disposal unit cost that has been reported thus far does not include such social cost. Figs. 1–3 show the material flow for the three nuclear fuel cycle options that were considered to calculate nuclear fuel cycle cost.

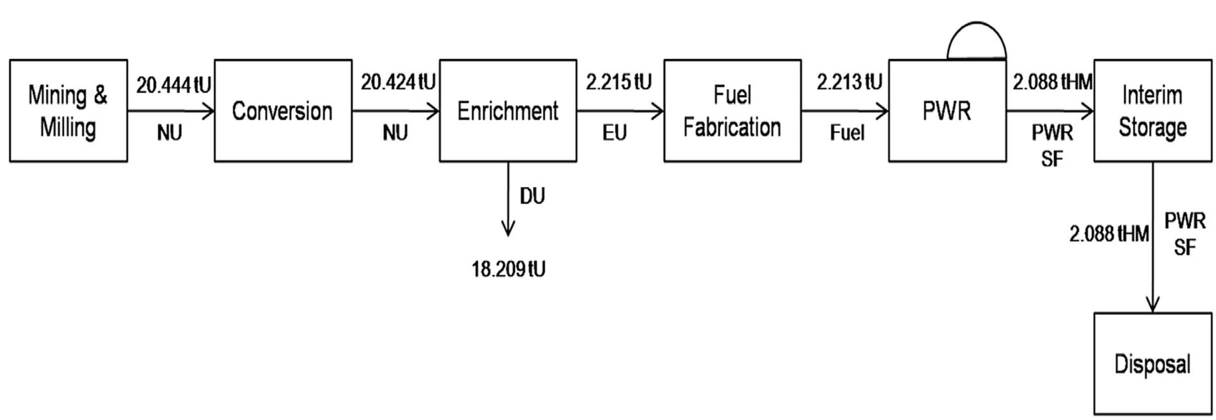

Fig. 1 – Once-through (OT) cycle. NU : Natural Uranium; EU : Enriched Uranium; DU : Depleted Uranium; PWR SF : Pressurized Water Reactor Spent Fuel.

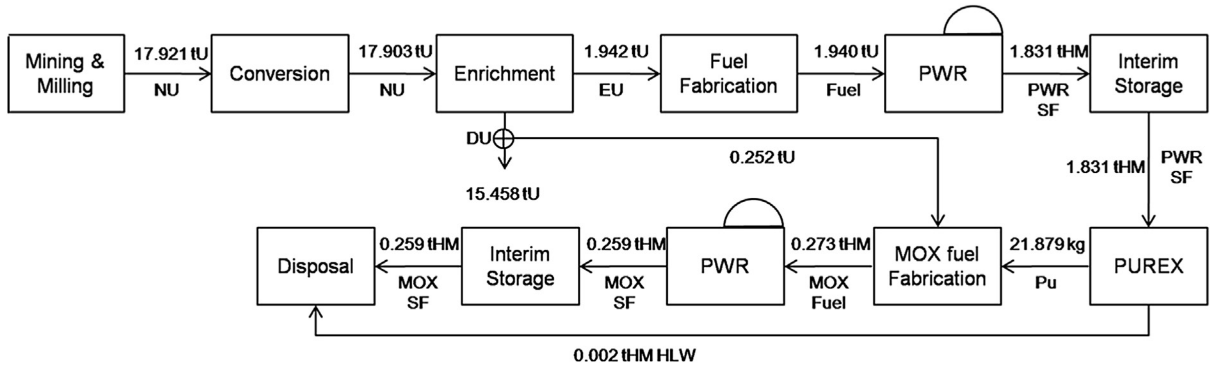

Fig. 2 – PWR-MOX recycling. MOX, mixed oxide (UO_2 and PuO_2) fuel; PWR, pressurized water reactor. MOX SF : Mixed OXide(UO2 and PuO2) Spent Fuel; PUREX : Plutonium-URanium EXtraction; HLW : High-Level Waste.

2.2. *Cost estimation models*

The models that can be used to evaluate the nuclear fuel cycle cost are the equilibrium model and the dynamic model [9].

The largest difference between the equilibrium model and the dynamic model is whether time-dependent information can be produced or not, because the time subject to evaluation is flexible. Namely, they can be divided into an equilibrium model that can produce only cost information at a certain time and a dynamic model that can calculate the cost tendency for the long term simultaneously.

While the dynamic model can calculate the material flow and cost of the nuclear fuel cycle facility in each year as time elapses, the equilibrium model can calculate the material flow and cost of the nuclear fuel cycle facility at a certain time.

Furthermore, the equilibrium model used is usually based on a factor study, but a dynamic model is mainly used for a logical study. Thus, while the dynamic model can apply feedback to the prior and back-end relations of the event, the equilibrium model can be copied for only a static status.

The two models (equilibrium model and dynamic model) are efficient tools to evaluate the economic efficiency of the nuclear fuel cycle option. The merit of the equilibrium model is to easily analyze the economic efficiency of certain nuclear fuel cycle options, roughly and quantitatively, by assuming a stable status. However, its demerit is an inability to calculate the tendency of long-term cost fluctuation simultaneously. Thus, it is mainly used to roughly grasp whether the cost of a certain nuclear fuel cycle alternative is relatively economical.

This study used the equilibrium model by considering the high uncertainty of nuclear fuel cycle unit cost and the convenience of calculation, because the result of a distorted calculation can be drawn by estimating the annual cost of high uncertainty for a long time through the dynamic model.

The equilibrium model draws rough information helpful to decision making at a certain time to generally produce information necessary to establish the policy of the nuclear fuel cycle. When the equilibrium model is used to calculate the nuclear fuel cycle cost, the general procedure is composed of the following phases. First, the material flow of the considered nuclear fuel cycle option is calculated. Second, the process cost spent in each phase of the nuclear fuel cycle is calculated by multiplying the material quantity and unit cost on the basis of the material flow, and then the cost of all process phases is summed to calculate the total cost of the nuclear fuel cycle. Third, the total cost of the nuclear fuel cycle is divided by the generation quantity to obtain the unit cost of the nuclear fuel cycle. Fourth, the most economical nuclear fuel cycle option can be drawn by comparing the total cost and unit cost of each nuclear fuel cycle option.

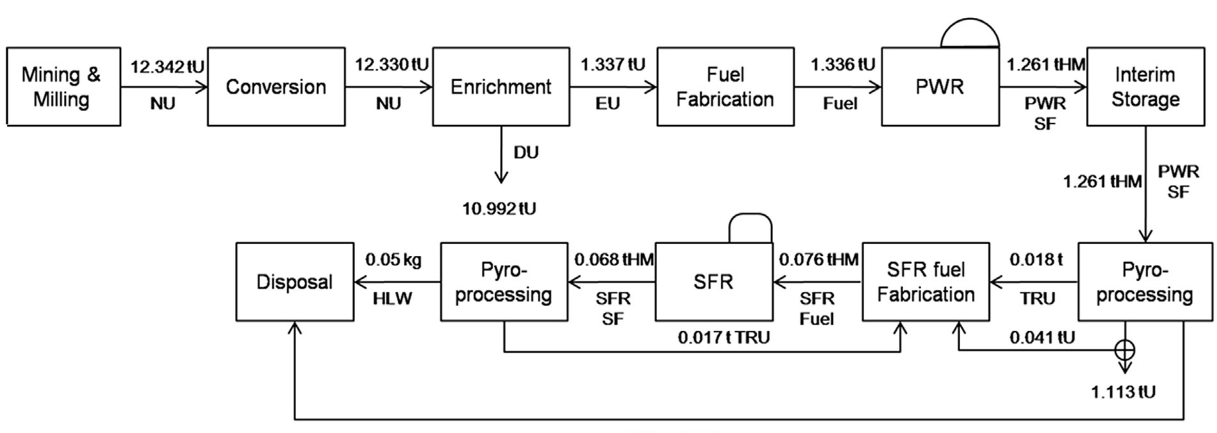

Fig. 3 – Pyro-SFR recycling. SFR : Sodium-cooled Fast Reactor; TRU : Trans Uranium.

Table 1 – Equations for the nuclear fuel cycle cost estimation using an equilibrium model.

Category	Equations	
Quantity of fabrication	$Qf(t) = \frac{C_s}{N_b}, \quad t = batch$	(1)
Quantity of enrichment	$Qe(t) = \left[V(EL) + \left(\frac{EL - T_a}{NAT - T_a} - 1\right) \cdot V(T_a) - \frac{EL - T_a}{NAT - T_a} V(NAT)\right] Qf(t)(1 + LFf)$	(2)
Quantity of conversion	$Qc(t) = \frac{EL - T_a}{NAT - T_a} Qf(t)(1 + LFf)$	(3)
Quantity of uranium	$Qu(t) = Qc(t)(1 + LFc)$	(4)
Cost of uranium	$Cu = Qu(t) \cdot UCu$	(5)
Cost of conversion	$Cc = Qc(t) \cdot UCc$	(6)
Cost of enrichment	$Ce = Qe(t) \cdot UCe$	(7)
Cost of fabrication	$Cf = Qf(t) \cdot UCf$	(8)
Cost of transportation; applied LAG time	$Ct = Qsf(t) \cdot UCt$	(9)
Cost of storage	$Cs = Qsf(t) \cdot UCs$	(10)
Cost of disposal	$Cd = Qsf(t) \cdot UCd$	(11)
Cost of reprocessing	$Cr = Qsf(t) \cdot UCr$	(12)
Total cost of direct disposal alternatives	$CTd(t) = Cu(t) + Cc(t) + Ce(t) + Cf(t) + Ct(t) + Cs(t) + Cd(t)$	(13)
Total cost of reprocessing alternatives	$CTr(t) = Cu(t) + Cc(t) + Ce(t) + Cf(t) + Ct(t) + Cs(t) + Cr(t) + Cd(t)$	(14)

Cd(t), disposal cost; Cs, core size; Cc(t), conversion cost; Ce(t), enrichment cost; Cf(t), fabrication cost; Cr(t), reprocessing cost; Cs(t), storage cost; CTd(t), total cost of direct disposal alternatives; CTr(t), total cost of reprocessing alternatives; Ct(t), transportation cost; Cu, cost of uranium; Cu(t), uranium cost; EL, enrichment; $V(x) = (2x-1)\ln\frac{x}{1-x}$;$LFc$, loss factor of conversion; LFf, loss factor of fabrication; NAT, natural uranium enrichment; Nb, No. of batches; Qu(t), quantity of uranium; t, years; T_a. tail assay enrichment; UCu, unit cost of uranium.

The equilibrium model based on the assumption of a stable status needs some basic premises. Namely, that the reference reactor and the nuclear fuel cycle facility already exist and that the reactor type is of the reasonable ratio and in complete operation status.

Although the time required to reach equilibrium status, and the restriction in technical development of the nuclear fuel cycle, cannot be reflected in the equilibrium model, the equilibrium model has a notable merit, i.e., to easily analyze the merits and demerits of the nuclear fuel cycle options quantitatively. Therefore, the equilibrium model can promptly provide a decision maker with some cost information related to the nuclear fuel cycle. Thus, the goal of the equilibrium model is to produce general information that is helpful to understand diverse nuclear fuel cycles systematically and comprehensively.

The largest limit of the equilibrium model is that it does not consider the change in the unit cost of the nuclear fuel cycle process. Namely, the equilibrium model can calculate the unit cost of the nuclear fuel cycle at a certain time only.

The total cost of the nuclear fuel cycle is generally calculated by multiplying the process quantity in each phase of the nuclear fuel cycle process with the unit cost [10]. Furthermore, the unit cost of the nuclear fuel cycle can be acquired by dividing the total cost of the nuclear fuel cycle by the generation quantity with the levelized cost estimation method [11].

If the future nuclear fuel cycle cost is calculated as a nominal value, it is converted to the present cost by applying the nominal discount rate. However, if it is calculated as a constant value, it can be converted into the present cost using the real discount rate [12].

Unless there are a lot of data on the process unit cost of a particular nuclear fuel cycle at present, it can be converted into the process unit cost of the nuclear fuel cycle of the desired year by using past data. Then, the escalation is used as the conversion factor.

Table 2 – Descriptive statistics of fuel cycle unit cost using 10,000 random sampling with Monte-Carlo method.

Phase	Value					
	Minimum	Maximum	Mean	Mode	Median	SD
Uranium	30.56	257.99	121.67	76.08	114.14	49.77
Conversion	5.0009	14.9994	10.00	14.75	9.99	2.8869
Enrichment	85.003	134.999	110.00	88.75	109.997	14.434
UO_2 fuel fabrication	200.264	299.353	250.00	249.749	249.999	20.414
Pyroprocess and SFR fuel fabrication	3,037.86	8,981.57	6,000.00	5,984.93	5,999.90	1,224.81
UO_2 S/F dry storage	100.25	299.10	173.33	121.51	165.82	44.97
UO_2 S/F packing	50.274	129.906	91.00	92.90	91.469	16.346
Disposal	403.72	996.58	683.33	649.50	675.95	123.05

SD, standard deviation; SFR, sodium-cooled fast reactor; S/F, spent fuel.

If the cost occurrence times vary in each option, the concept of the average cost is used to judge the relative economic efficiency of each nuclear fuel cycle option. Such nuclear fuel cycle cost is called the levelized unit cost. It is often used as ground data when evaluating the economic efficiency of each nuclear fuel cycle option.

As this study used the equilibrium model to calculate the cost at a certain time, the nuclear fuel cycle cost is calculated by using Eqs. 1–14 in Table 1, which does not consider the discount rate.

Because the equilibrium model used in this study calculates the cost at a certain time, it is unnecessary to discount the yearly cost. Thus, the equilibrium model can be drawn to easily calculate the nuclear fuel cycle cost, if assuming the discount rate is 0 [13].

3. Results : comparative analysis of the results of the calculating cost

3.1. *Input data*

Generally, the economic efficiency of the nuclear fuel cycle is set on the basis of direct disposal and evaluated using the relative rate of nuclear fuel cycle costs, because direct disposal is known to be economically efficient [4].

As the technology related to the nuclear fuel cycle can be developed later, the unit cost in each phase of the process can change, and such change should be reflected in the nuclear fuel cycle cost. For instance, the disposal unit cost or the pyroprocess unit cost will be reduced as SF disposal technology or pyroprocess technology is developed. A more precise cost evaluation model should be developed to reflect such cost reduction. To this end, cost drivers should be grasped exactly, and the cost pool of costly processes should be subdivided, because the nuclear fuel cycle cost can be calculated more exactly by converting an indirect cost into a direct cost [14].

Since the unit cost for each nuclear fuel cycle process is drawn from the environment varying in each state, data should be normalized first to reduce the uncertainty of the cost data and to increase the reliability of the calculation results. If the economic efficiency of the nuclear fuel cycle option is evaluated using the unit cost without normalization, the result of the evaluation can be distorted. Thus, cost data should be normalized by analyzing the main factor that causes uncertainty. This study used @Risk software (Palisade corporation, www.palisade.com) to draw the probability distribution function of the normalized estimated cost [15]. Further, the feasibility of the probability distribution was confirmed using the goodness of fit method of SPSS software (Statistics version 21) (SPSS Inc., Chicago, IL, USA) [16], and the probability distribution of the unit cost of the nuclear

Table 3 – Probability distribution function of fuel cycle unit cost.

Phase	Probability distribution	Value			Unit	Remarks
		Low	Nominal	High		
Uranium	Triangular	30	75	260	\$/kgU (U_3O_8)	Spot market prices as of March 2012
Conversion	Uniform	5	10	15	\$/kgU (UF_6)	Spot market prices as of March 2012
Enrichment	Uniform	85	110	135	\$/SWU	Spot market prices as of March 2012
Fabrication (PWR)	Triangular	200	250	300	\$/kgU	OECD/NEA report (2006)
Aqueous storage	Triangular	100	300	500	\$/kgHM	OECD/NEA report (2006)
S/F dry storage	Triangular	100	120	300	\$/kgHM	OECD/NEA report (2006)
Pyroprocess and SFR fuel fabrication	Triangular	3,000	6000	9,000	\$/kgHM	Advanced fuel cycle cost basis, INL report (2009)
UREX aqueous separation	Triangular	903	1,120	1,339	\$/kgHM	OECD/NEA report (2006)
S/F conditioning and packaging	Triangular	50	93	130	\$K/MTHM	OECD/NEA report (2006)
S/F geologic repository	Triangular	400	650	1,000	\$/kgHM	OECD/NEA report (2006)
Transport (PWR SF)	Triangular	55	69	90	\$/kgHM	Hyundai Engineering report (2009)

INL, Idaho National Laboratory; NEA, Nuclear Energy Agency; OECD, Organization for Economic Co-operation and Development; PWR, pressurized water reactor; SF, spent fuel; SFR, sodium-cooled fast reactor.

Table 4 – Input parameters of reference reactor.

Reactor parameters	PWR	SFR (CR = 0.70)
Electric power (MWe)	1,000	600
Thermal efficiency (%)	34.23	39.4
Thermal power (MWt)	2,921.40	1,522.8
Load factor	0.85	0.85
Cycle length (full power day)	290	304
Number of batches	3	5

CR, conversion ratio; PWR, pressurized water reactor; SFR, sodium-cooled fast reactor.

fuel cycle in Table 2 was drawn by referring to Table 3 [24,25]. In addition, the parameters of standard deviation were calculated for the sensitivity analysis of unit costs.

Generally, the reliability of data on the cost of nuclear fuel cycles is verified from the following three viewpoints. First, whether the data were measured by a reliable method; second, whether the utility and limit of cost information were specified; and third, whether the evaluation of uncertainty by analyzing the sensitivity was identified [17].

It is also necessary to check the detailed level of data to keep the quality of each data set and determine whether consistent ground data were used [18]. Then, an independent review of the data should be conducted. The reference reactor used in this study and the input variable of the nuclear fuel cycle are indicated in Tables 4 and 5; and the reactor cost was referred from the Organization for Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA) report [19].

3.2. *Result of calculating a deterministic nuclear fuel cycle cost*

The result of calculating the nuclear fuel cycle cost using the deterministic method is shown in Table 6, and the most likely value in Table 2 was used as the unit cost of each fuel cycle process. The NFCC (Nuclear Fuel Cycle Cost estimation program) Version 01 code developed by the KAERI (Korea Atomic Energy Research Institute, Daejeon, Korea) is used to calculate the fuel cycle cost.

According to the calculation, the direct disposal cost and Pyro-SFR nuclear fuel cycle cost including reactor cost were found to be 66.41 mills/kWh and 77.82 mills/kWh

Table 6 – Fuel cycle cost and reactor cost (unit: mills/kWh).

Item	PWR-OT	PWR-MOX	Pyro-SFR
Uranium	3.067	1.988	1.851
Conversion	0.204	0.179	0.123
Enrichment	1.674	1.568	1.011
Fabrication (UO2)	0.554	0.785	0.334
S/F transportation	0.43	0.29	0.26
Wet reprocessing		1.951	
MOX Fab.		1.897	
Pyroprocessing for PWR SF			1.769
Metal fuel fab.			1.851
SF storage	0.376	0.330	0.327
SF disposal	1.972	0.519	
HLW storage		0.052	0.029
HLW disposal		0.108	0.506
Sub-total (fuel cycle cost)	8.277	9.667	8.061
Reactor cost	58.13	58.13	69.756
Total (generation cost)	66.407	67.797	77.817

HLW, high-level waste; MOX, mixed oxide (UO_2 and PuO_2) fuel; OT, once-through; PWR, pressurized water reactor; SF, spent fuel; SFR, sodium-cooled fast reactor.

(1 mill = 1,000 of a dollar, i.e., 10^{-3} \$). Therefore, the direct disposal is found to be the most economical alternative, followed by the Pyro-SFR nuclear fuel cycle.

3.3. *Result of calculating the probabilistic nuclear fuel cycle cost*

The unit cost in each phase of the nuclear fuel cycle, as the estimated cost instead of the real cost, is used as input data to evaluate the economic efficiency of the nuclear fuel cycle. Thus, the uncertainty of the unit cost can absolutely affect the overestimate or underestimate of the nuclear fuel cycle cost [20]. Therefore, it is necessary to calculate the probabilistic cost so as to provide the decision maker of the nuclear fuel cycle policy with more useful information.

A triangular distribution function, uniform distribution function, and normal distribution function are generally used as a distribution function for the unit cost of each phase of the nuclear fuel cycle to calculate the probabilistic fuel cycle cost. A triangular distribution is used when the maximum value, minimum value, and the most likely value are known, and a uniform distribution is used when the maximum value and

Table 5 – Input parameters of the fuel cycles.

Fuel cycle	OT	PWR (MOX)	Pyro-SFR (TRU)
Enrichment	NU: 0.71% ^{235}U DU: 0.25% ^{235}U EU: 4.5% ^{235}U	NU: 0.71% ^{235}U DU: 0.25% ^{235}U EU: 4.5% ^{235}U	NU: 0.71% ^{235}U DU: 0.25% ^{235}U EU: 4.5% ^{235}U
PWR fuel Burnup (UO_2)	55 GWd/tHM	55 GWd/tHM	55 GWd/tHM
Back-end for PWR SF	–	PUREX Loss: 0.1% Major waste: MA, FP	Pyroprocessing Loss: 0.1% Major waste: FP
MOX PWR fuel	–	Burnup: 55 GWd/tHM Pu: 8%	–

DU, depleted uranium; EU, enriched uranium; FP, fission product; HM, heavy metal; MOX, mixed oxide fuel; NU, natural uranium; OT, once-through; PWR, pressurized water reactor; PUREX, plutonium-uranium extraction; SFR, sodium-cooled fast reactor; TRU, trans uranium.

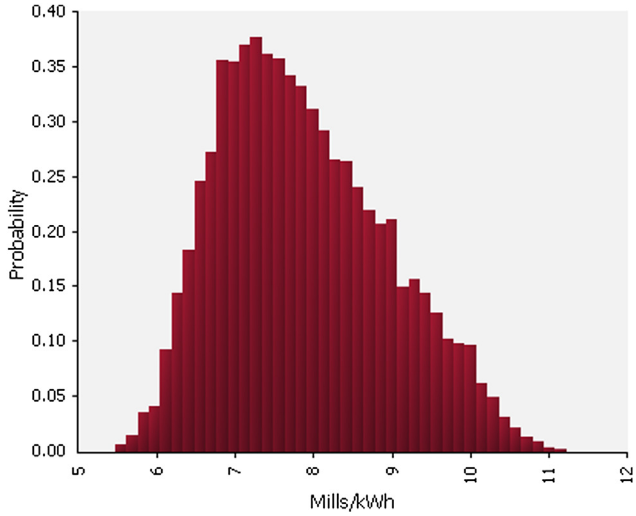

Fig. 4 – Direct disposal cost.

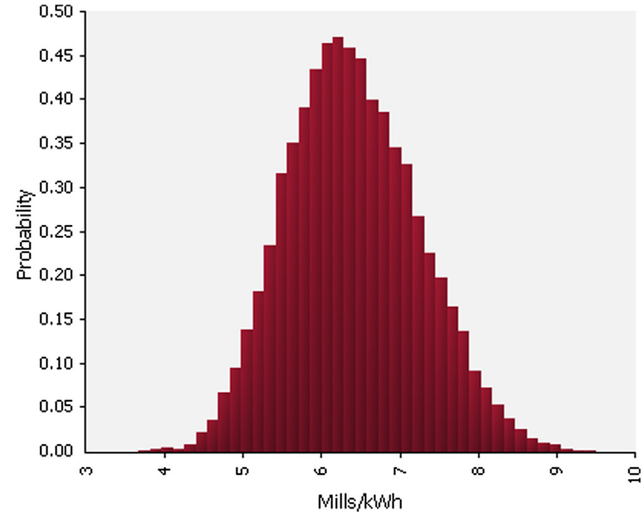

Fig. 6 – Pyro-SFR fuel cycle cost. SFR, sodium-cooled fast reactor.

minimum value are known, but the most likely value is unknown [21].

Calculating the nuclear fuel cycle cost by the probabilistic method with the distribution function value of the fuel cycle unit cost in Table 2, the nuclear fuel cycle cost of each option is indicated in Figs. 4–6. This can provide decision makers with some information about the uncertainty of nuclear fuel cycle costs.

The descriptive statistics are indicated in Table 7. Fitting the distribution function of the nuclear fuel cycle cost using @Risk software, it was found to be proximate to the Beta distribution. By calculating the nuclear fuel cycle cost by a probabilistic method, the nuclear fuel cycle cost of direct disposal and Pyro-SFR, except for the reactor cost, were finally found to be 7.47 mills/kWh and 6.40 mills/kWh on the basis of the most likely value. Namely, the Pyro-SFR nuclear fuel cycle was evaluated to be a more favorable option than direct disposal. However, if the reactor cost was considered, the result is opposite to the result found by calculating the nuclear fuel cycle cost by the deterministic method by inputting the most likely value of the unit cost in Table 3.

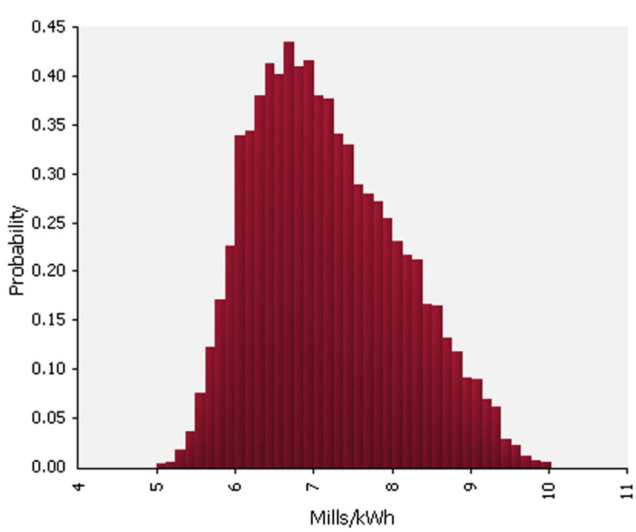

Fig. 5 – PWR-MOX fuel cycle cost. MOX, mixed oxide (UO_2 and PuO_2) fuel; PWR, pressurized water reactor.

4. Sensitivity analysis

The regression coefficient of the unit cost was calculated by using @Risk software to clarify the factors of the unit cost that considerably affect the nuclear fuel cycle cost [22].

The influence of the uncertainty of the unit cost on the nuclear fuel cycle cost can be calculated using a contribution to variance, as shown in Eq. (15) [20]:

$$CV_i = \frac{(CCX_i)^2}{\sum_i (CCX_i)^2} \quad (15)$$

where CV_i = contribution to variance at phase i, and CCX_i = correlation coefficient of X variable at phase i.

The sensitivity analysis conducted to analyze the influence that the unit cost in each phase of the fuel cycle process has on the nuclear fuel cycle cost showed that the uranium cost is the most influential factor on the nuclear fuel cycle cost in all

Table 7 – The probabilistic cost estimation results for three fuel cycle options (unit: mills/kWh).

Category	OT	PWR-MOX	Pyro-SFR
Minimum	5.4682	4.9882	3.6691
Maximum	11.2345	10.0359	9.5021
Mean	7.8772	7.1854	6.4110
Mode	7.4740	6.4688	6.3971
Median	7.7429	7.0654	6.3658
SD	1.0654	0.9326	0.8357
Skewness	0.4225	0.4202	0.2187

MOX, mixed oxide (UO_2 and PuO_2) fuel; OT, once-through; PWR, pressurized water reactor; SD, standard deviation; SFR, sodium-cooled fast reactor.

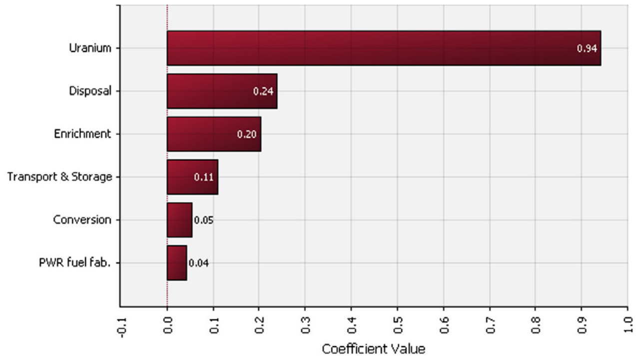

Fig. 7 – Sensitivity of direct disposal unit cost.

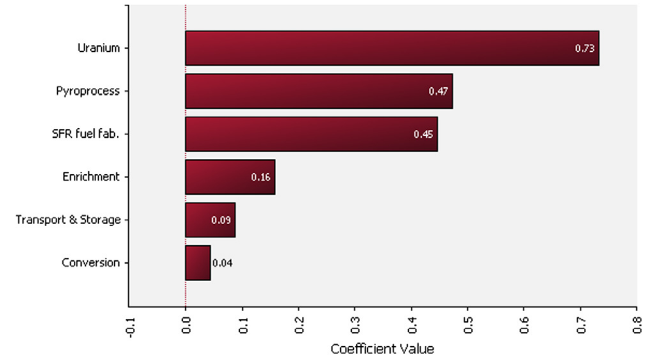

Fig. 9 – Sensitivity of Pyro-SFR fuel cycle unit cost. SFR, sodium-cooled fast reactor.

three options, as shown in Figs. 7–9. In particular, the disposal unit cost was found to be the second influential factor after uranium costs in the direct disposal option of Fig. 7. As shown in Fig. 9, the Pyroprocess unit cost was found to be the influential factor in the Pyro-SFR fuel cycle option. Thus, the disposal technology and Pyroprocess technology should be constantly developed to reduce the nuclear fuel cycle cost.

5. Conclusion and discussion

The nuclear fuel cycle cost of three options (Pyro-SFR, PWR-MOX, and direct disposal) was calculated by two methods (deterministic method and probabilistic method) with the equilibrium model.

If the probabilistic method is used, the nuclear fuel cycle cost of direct disposal and Pyro-SFR (excluding the reactor cost) are found to be 7.47 mills/kWh and 6.40 mills/kWh, respectively, on the basis of the most likely value. Therefore, the Pyro-SFR nuclear fuel cycle option is the most economical in the probabilistic method that uses the probability distribution value. However, after considering the reactor cost, the generation costs of the direct disposal option and the Pyro-SFR nuclear fuel cycle option in the deterministic method are found to be 66.41 mills/kWh and 77.82 mills/kWh, respectively. Such difference may be caused by the fact that the SFR cost is considerably expensive [19].

In addition, many differences were found between the results of the calculating cost by using the deterministic input value, and that of the calculating cost using the probabilistic input value, although the same equilibrium model was used. Thus, it is judged that the probabilistic nuclear fuel cycle cost should be evaluated by reflecting the uncertainty.

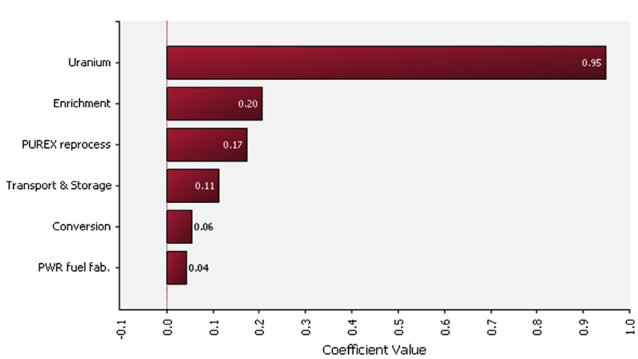

Fig. 8 – Sensitivity of PWR-MOX fuel cycle unit cost. MOX, mixed oxide (UO_2 and PuO_2) fuel; PWR, pressurized water reactor.

Further, decision making related to the policy of the nuclear fuel cycle is related to the propensity of the decision maker. If a risk-loving decision maker has nuclear fuel cycle cost information calculated by the probabilistic method, the deviation of the nuclear fuel cycle cost will be large, but the low-cost alternative would be preferred. However, a risk-avoiding decision maker will prefer an alternative with a relatively high cost, but a low cost deviation [23].

Analyzing the sensitivity of the nuclear fuel cycle process on the unit cost, the uranium cost is found to be the most influential factor in all three options. In the case of direct disposal and the Pyro-SFR fuel cycle option, the disposal unit cost and Pyroprocess unit cost are found to be influential factors after the uranium cost. This may be caused by the fact that the deviation of probability distribution of the relevant unit cost is relatively large.

Particularly in the case of the direct disposal option, the uncertainty of the nuclear fuel cycle cost is increased when reflecting the social cost to acquire the repository site. Thus, a probabilistic cost calculation will be more necessary.

However, the equilibrium model used in this study is subject to a limitation, that is, the inability to calculate time-dependent material flow and cost. It may be necessary to develop a dynamic model later to comparatively analyze the results of the calculation of the equilibrium model and the dynamic model.

Conflicts of interest

All authors declare no conflicts of interest.

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